DEVELOPMENT OF INSTRUMENTED OEDOMETER INCORPORATED WITH BENDER ELEMENT AND ELECTRICAL CONDUCTIVITY

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Praised to Allah. Sincerely dedicated to my beloved parents, brothers and wife…

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ABSTRACT

Soft soils are normally associated with high moisture content and fine-grained particles possessing poor geotechnical properties such as low shear strength and high compressibility. Solidification, using hydraulic binders could be adopted to improve these poor properties. The compressibility of soil is quantified by the settlement reduction due to the application of vertical load. Usually, the compressibility test is conducted on undisturbed saturated soils using standardised oedometer. In this study, an instrumented oedometer was developed by incorporating bender element transducers and electrical conductivity probe to investigate and correlate the compressibility, shear wave velocity (V_s) and electrical conductivity (EC) characteristics of solidified dredged marine clay and refined kaolin. Ordinary Portland cement was used at 5 %, 10 % and 15 % by dry weight of soil as a solidification agent. All specimens were mixed at twice the liquid limit. Prior to testing, all solidified specimens were cured for 7 days. It was found that V_s increased continuously with further curing time whereas EC increased during the first day and decreased with further curing. The compressibility was reduced and yield stress was developed as the cement content increased. V_s and EC showed good correlation with applied stress during the loading stage as the strain increased. For all loading stages, V_s increased when the strain increased while EC decreased as the strain increased. Similarly, V_s, EC and e showed good relationship as the vertical stress increased. These results showed good relationship and strong correlations between the compressibility parameters and V_s and EC measurements which give some insights on the solidification mechanism and improvement of stiffness. These results also confirmed that the instrumented oedometer incorporated with bender element and electrical conductivity probes can be applied on soft soils to monitor the compressibility behaviour at micro level. Moreover, the obtained relationships could be adopted in numerical modelling as well design analysis of similar soils in situ.

ABSTRAK

Tanah lembut lazim dikaitkan dengan kandungan lembapan yang tinggi dan zarah-zarah tanah yang halus dengan sifat geoteknik yang lemah, yakni kekuatan ricih yang rendah dan kebolehmampatan yang tinggi. Solidifikasi tanah dengan menggunakan bahan tambah hidraulik boleh diaplikasikan untuk menambahbaik sifat tanah yang lemah ini. Kebolehmampatan tanah dianggarkan melalui pengurangan enapan akibat aplikasi beban tegak. Lazimnya, ujian pengukuhan dijalankan ke atas sampel tanah tak terusik dengan alat oedometer piawai. Dalam kajian ini, sebuah oedometer yang diubahsuai dengan menambah alat 'bender elements' dan proba kebolehaliran elektrik telah dibangunkan untuk mengkaji hubungan di antara parameter kebolehenapan, halaju gelombang ricih (V_s) serta kebolehaliran elektrik (EC) bagi tanah liat kerukan marin dan kaolin yang disolidifikasikan. Simen Portland biasa ditambah sebagai bahan pengikat pada kadar 5%, 10% dan 15% daripada jisim kering tanah. Semua spesimen telah disediakan pada kandungan lembapan 2 kali ganda had cecair tanah. Sebelum ujian dijalankan, spesimen dibiarkan untuk mengawet selama 7 hari. Adalah didapati bahawa V_s meningkat secara berterusan dengan tempoh pengawetan, manakala EC hanya meningkat pada hari pertama dan disusuli penurunan dengan pengawetan. Kebolehenapan didapati menurun dan tegasan alah meningkat dengan penambahan kandungan simen. V_s dan EC menunjukkan korelasi yang baik dengan tegasan yang dikenakan semasa pembebanan dan peningkatan terikan. Untuk kesemua peringkat pembebanan, V_s meningkat dan EC menurun dengan peningkatan terikan. Juga, V_s, EC dan e menunjukkan korelasi yang baik dengan peningkatan tegasan tegak. Keputusan yang diperolehi menggambarkan korelasi yang baik di antara parameter kebolehenapan serta V_s dan EC, yang mencerminkan mekanisme solidifikasi dan penambahbaikan sifat kekukuhan tanah tersebut. Keputusan ini juga mengesahkan korelasi ini boleh juga digunapakai dalam menyediakan model numerikal serta reka bentuk analisis tanah lembut serupa di tapak. Juga bahawa Oedometer yang diubahsuai

dengan menambah alat “bender elements” dan proba keboleh aliran elektrik boleh digunrakan ke atas tanah lembut untuk memantau kebolehenapan pada tahap mikro.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

A	-	Al_2O_3
AL	-	Atterberg limit
BE	-	Bender Element
C	-	Ca
CAH	-	Calcium Aluminate Hydrate
CASH	-	Calcium Silicate Hydrate
C_c	-	Compression Index
R	-	Correlation Coefficient
C_v	-	Coefficient of Consolidation
C3A	-	Tricalcium Aluminate
C4AF	-	Tetracalcium Aluminoferrite
CSH	-	Calcium Silicate Hydrate
C2S	-	Dicalcium Silicate
C3S	-	Tricalcium Silicate
DMS	-	Dredged Marine Soil
e	-	Void Ratio
EC	-	Electrical Conductivity
F	-	Fe_2O_3
GDS	-	Global Digital Systems Ltd
IOC	-	Instrumented Oedometer Test
Kg	-	Kilogram
KPa	-	Kilopascal
LL	-	Liquid Limit
LOI	-	Loss of Ignition
MC	-	Moisture Content

M_v	-	Coefficient of Volume Compressibility
OMC	-	Organic Matter Content
PI	-	Plasticity Index
PL	-	Plastic Limit
PSD	-	Particle Size Distribution
S	-	SiO_2
T_{50}	-	Time Corresponding to 50 % Settlement
V_s	-	Shear Wave Velocity
XRD	-	X-Ray Diffraction
XRF	-	X-Ray Fluorescence
σ'	-	Vertical Effective Stress
ε	-	Vertical Strain
ρ	-	Particle Density

CHAPTER 1

INTRODUCTION

Marine dredging is a process of excavating sediments from the bottom of waterbodies by mechanical or hydraulic machineries. The common purposes of marine dredging are to make waterways for marine vessels navigation, coastal development projects, and removal of contaminated sediments. There are two methods for disposal; open water dumping and inland disposal. However, there are harmful environmental consequences associated with each method. For instance, coral reefs, flora-fauna and benthic organism could be affected directly by burial or indirectly by smothering (Katsiaras *et al*., 2015). Moreover, finding a place inland is a challenge and there is always a concern of contamination leaching to the groundwater table.

The normal practice in Malaysia is open water dumping which is restricted in more advanced countries. Instead of dumping, these countries started utilising these materials for beneficial purposes in civil engineering construction i.e. land reclamation. However, the challenge for fine grained dredged marine soil is the high moisture content and the presence of a considerable amount of organic matters making direct use impossible due to the high compressibility and low shear strength. Therefore, appropriate treatment must be adopted to reduce DMS compressibility. Solidification technique could be adopted to reduce the compressibility. Past research on soft soil have found that hydraulic binders (i.e. cement) and other pozzolanic by-products (i.e. coal ash, steel slag) could successfully solidify and stabilise soft soils. Usually 1-D consolidation test is conducted to evaluate the compressibility.

Conventional oedometer has been used to test compressibility primarily for undisturbed saturated fine-grained soils in laboratory. Although, the outcomes of the test are useful in drawing the relationship between the applied vertical stress and the associated 1-D consolidation deformation, but it didn't give information about the mechanism of consolidation.

Bender elements are piezoelectric transducers that can produce compression waves and shear waves. Shear waves propagate through the solid medium while the compression wave propagates through both solid and liquid. Thus, shear wave is commonly used for soil stiffness assessment. It has the advantage of giving some insights about small strain stiffness in the range of 10^{-6} and hence the interparticle state of the soil. Since its first introduction to the soil testing by Shirley & Anderson (1975), it has been showing promising indications of the inner state of soil particularly small strain stiffness. Even though there is an agreement of its usefulness in determining the small strain stiffness, it is worth mentioning that some obstacles have been faced related to the results interpretation which hindered global standardisation, (such as arrival time interpretation, near field effects).

Other non-destructive measurements are useful in quantifying the state of soil without disturbing. In geophysics, however, there were attempts of utilising these techniques to evaluate the soil. Yet, it couldn't replace the conventional destructive measurements due to the particulate nature of the soil. Nevertheless, it can give useful insights on the soil behaviour in micro level. Electromagnetic and electrical conductivity / resistivity deal with the pore fluid and surface charges of the soil. Hence, it complements the shear wave velocity paralleled with the 1D consolidation especially in evaluating the compressibility of the solidified soft soil.

1.1 Problem statement

Soft soils are normally associated with high moisture content and fine-grained particles resulting in poor geotechnical properties such as high compressibility and low shear strength. DMS is a truly example of such soil which requires proper treatment to be useable for beneficial purposes (i.e. reclamation works as fill materials). Solidification/stabilisation of these soils using hydraulic binders (i.e. cement) is usually conducted to improve these poor properties. The conventional oedometer test is designed to test the compressibility of undisturbed saturated fine-grained soil. However, the specimen's preparation of soils in slurry form using the conventional setup is impractical with inadequate travel distance for the expected large settlement. Furthermore, the solidification mechanism and consolidation of the soil is still not well-understood which requires more investigations. Therefore, modification for the conventional oedometer is required with additional tools to monitor the solidification and consolidation processes. Invasive and minimally invasive testing techniques for geotechnical engineering purposes, nowadays, are developing progressively. Nonetheless, due to the particulate nature of soil, there exists a transitional zone where the conventional testing (macro-level), which is the compressibility in this study, is studied simultaneously in micro-level using these techniques. For this purpose, an instrumented oedometer test was developed with incorporation of bender element (BE) transducers and electrical conductivity probe to investigate and correlate the compressibility, shear wave velocity (V_s) and electrical conductivity (EC) characteristics of solidified dredged marine clay and refined kaolin. The advantage of using BE is that it can measure the small strain stiffness for less than 10^{-6} which can evaluate the inter-particle condition of cementation process whereas EC measurements can give an indication of the chemical reactions and water availability within cement-water-soil mixture.

1.2 Objectives of the research

The aim of this research is to investigate and correlate the compressibility, shear wave velocity and electrical conductivity characteristics of solidified fine-grained soils using an instrumented oedometer. The following objectives are to be achieved in the present study:

1. To develop an instrumented oedometer cell incorporated with electrical conductivity and bender elements measurements.
2. To investigate the one-dimensional compressibility of solidified DMS and kaolin in relation to the electrical conductivity and shear wave velocity measurements.
3. To establish the correlations between the electrical conductivity and shear wave velocity measurements with the improved compressibility of the tested soils.

1.3 Scope of Research

Based on the objectives of this study, the scope of study can be classified into two phases. The first phase is about the development of the instrumented oedometer. Modifications on the conventional oedometer were made considering enough travel distance for slurry soil to settle and providing enough space for the additional probes to be installed. One pair of BE was installed in the top cap and bottom platen, while the EC probe was installed on the top cap. GDS master box was used to operate the BE via computerised system.

The second phase is the implementation of the work. In this study two types of soils were used; dredged marine soil collected from Kuala Perlis and refined Malaysian kaolin clay. Ordinary Portland cement was used as solidification agents with 5 %, 10 % and 15 % by dry weight. Characterisations of the DMS and kaolin were conducted on the moisture content, plastic limit, liquid limit, particle density, LOI and XRF. After specimen preparation, the treated specimens were cured for 7 days prior to testing. The shear wave velocity was determined using bender element transducers and EC were taken during the curing time. Loading the soil incrementally and taking the BE and EC simultaneously with the settlement. Then, the relationship among these three parameters were investigated and the relationship between these parameters was established.

1.4 Significance of Study

The oedometer was modified to incorporate additional instrumentation which can help in understanding the mechanism of the compressibility of the solidified soil to assess the quality control. Moreover, the non-destructive testing is more desirable in geotechnical engineering. Instead of dumping the DMS into the open water, it could be used for beneficial purposes after proper treatment. Hence, two things can be achieved: (1) to avoid bad environmental consequences caused by dumping and (2) utilise DMS instead of natural resources by adopting the solidification technique to improve the compressibility of this soils to be used for reclamation hence providing more areas/land especially at places where more space is needed such as recreational spots (i.e. Dubai) and creating new infrastructures (i.e. airports in Japan).

1.5 Thesis Layout

Chapter one presents the background of study, problem statement, research objectives, scope of study, significance of study and theses layout.

Chapter two covers the literature review and results obtained by the previous related works. Review on previous studies on modified oedometers incorporating bender element and electrical conductivity measurements was providing in beginning of this chapter followed by bender element and electrical conductivity. One-dimensional consolidation test, treatments effects on compressibility, mechanism of solidification, curing time effects, yield stress, physicochemical, solidification agent and DMS were also reviewed in this chapter.

Chapter three describes the methodology, materials and experimental approach adopted to achieve the objectives of this study. The first part describes the instrumented oedometer and calibration. The second part describes the one-dimensional consolidation test and samples preparations. The third part describes the material used in this study followed by soils characterisation tests.

Chapter four presents the results and discussion in six subsections. The first part is about the cement effects on the moisture, V_s and EC during the specified curing period. The second part presents the compressibility parameters namely, void ratio, coefficient of consolidation, coefficient of volume compressibility and compression index. The third part is about the yield stress. The fourth and fifth part presents the relationship between the compressibility and V_s and EC respectively. The last section compares the correlation between the compressibility, V_s and EC parameters.

Chapter five concludes the results of the study and the recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter evaluates critically on oedometer test including standard, modified oedometers, bender element, electrical conductivity, soft soil treatment, physicochemical properties of soft soil and dredged marine soil are presented. In addition, a discussion of advanced analysis techniques of solidification is also presented.

2.1 Oedometer Test

The oedometer test is commonly used in soil mechanics to determine parameters for calculation of consolidation, settlement and for assessing stress history of soils.

2.1.1 Overview

As mentioned above, the oedometer consolidation test is used for the determination of the compressibility characteristics of soils with low permeability. There are two parameters required for this test: (1) The soil compressibility which is a measure of the amount by which the soil will compress when loaded and allowed to consolidate which can be expressed of the settlement or void ratio reduction. (2) The time related parameter which indicates the rate of compression and hence the time-period over which consolidation settlement will take place.

The test is conducted by applying a sequence of specified incremental vertical loads to a laterally confined specimen. The vertical compression under each load is observed until the primary consolidation is achieved. Since no lateral deformation is allowed, it is considered a one-dimensional test. The consolidation cell consists essentially of a consolidometer and a supporting frame as detailed in section 2.1.4.

2.1.2 Principle of Consolidation

The theory of consolidation states that the compressibility of solid particles and water can be negligible compared to the compressibility caused by the escaping of water. Consolidation is rapid in low permeable soils such as sand and slow in high permeable soils like clays hence requires longer time. Analogical illustration of the consolidation was introduced by Terzaghi & Peck (1948) and Taylor (1948). The process of consolidation is often explained with an idealized system composed of a spring in a container, filled with water, with a hole in its top cap as shown in Figure 2.1.

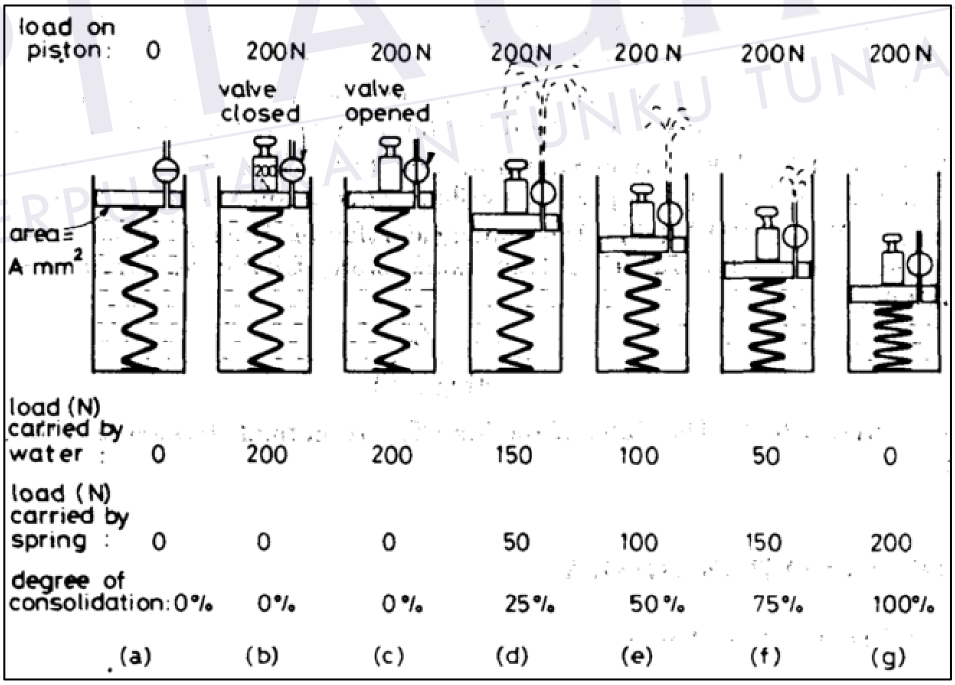

Figure 2.1: Spring and piston analogy illustrating the principle of consolidation (Taylor, 1948)

The spring represents the solid structure of the soil and the water represents the pore water in the soil. When applying a load on the top cap, while the hole is closed, the

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